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Pasonen, Riku

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RESEARCH REPORT

VTT-R-06945-18

Power plant lightning overvoltage protection of low voltage power electronics

Authors: Riku Pasonen

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Summary

The effects of direct lightning strike and flashover strike to 400kV system of nuclear power plant were inspected for perspective of low voltage power electronic devices. Protection methods were simulated with PSCAD transient simulator. The devices simulated were, metal oxide protector, three phase rectifier load and clamp style protection device with over-current protection and a battery. Metal oxide protector was effective to limit over voltage but some effects were noticed still at DC bus as a rise in bus voltage. The connection of power electronic load solely already limited the overvoltages in LV AC points near the load. This effect comes from capacitance in the load to buffer the rectifier voltage. There are also protective capacitors over the rectifier components(in this case diodes) to protect them from overvoltages and they also help to dampen the overvoltages at AC and DC bus. Battery also dampened the overvoltage so much that clamp type protection did not even activate. It has to be said that there is uncertainty of battery behaviour in very fast transient phenomena as most of measurements and models do not focus on this but it is very clear that dampening effect is considerable.

Results indicate that capacitors are very effective at damping fast transient overvoltages. Because most DC rectifiers are based on active bridge technologies, it is small effort to also include protective functionalities such as overvoltage and over-current protections. Although mechanical breakers are effective devices, they have operational delay for noticing the fault and acting. Therefore some passive protective methods could be used such as clamp type protection or additional capacitors. This study points to that capacitors are good solution for lightning overvoltage protection for power electronic devices. More broad usage of them in protection concept should be studied more on many other aspects such as potential contribution to faults in probabilistic manner.

Confidentiality	Public

Espoo 18.12.2018

Written by	Reviewed by	Accepted by
Riku Pasonen, Research Scientist	Seppo Hänninen, Senior Scientist	Tuula Mäkinen, Vice President

VTT's contact address

Teknologian tutkimuskeskus VTT Oy, PL 1000, 02044 VTT

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Preface

Work is continuation from previous phase of SAFIR programme where lightning strike was modelled with EMTP-ATP electromagnetic transient method. This work uses the result of voltage characteristics and simulates their effects on power electronic loads and protection. Thanks to Ari Kanera for constructive comments and reviewing the work.

Espoo 21.12.2018

Author

Contents

1. Introduction

Lightning overvoltage is one of the study areas of the ESSI project. A direct lightning strike to high voltage power lines was analysed by Deepak Subedi and Matti Lehtonen for general nuclear power plant model. This work uses the results of that study as base to investigate how low voltage devices such as power electronics should be protected from the phenomena. The main research question is that is there any sense to have DC protection in place for lightning overvoltage. Simplified circuit layout of the study is presented in Figure 1-1.

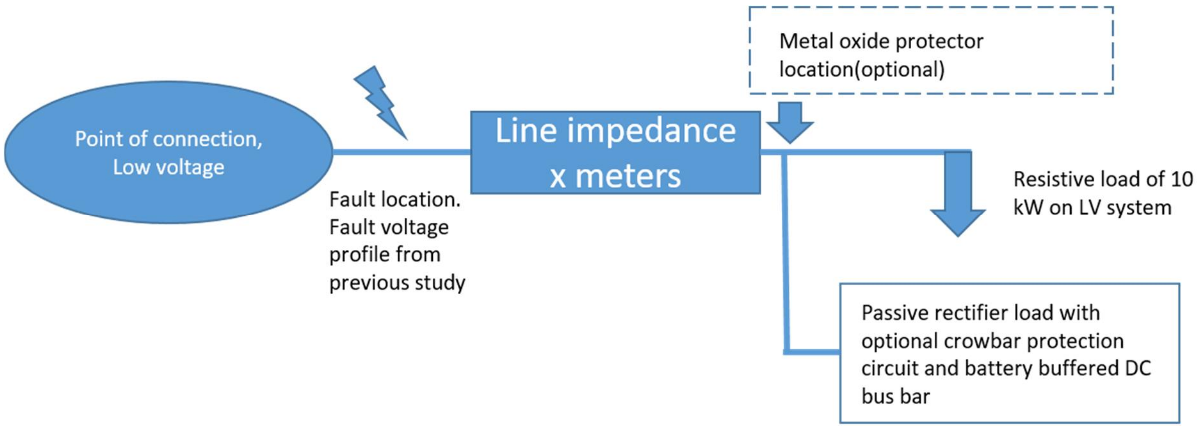

Figure 1-1: Simlified circuit layout of the simulation study

2. LV protection methods

Low voltage protection for overvoltage is usually done with power electronic surge arresters. Circuit is either opened or short circuited to protect load from overvoltage. Mechanical switches always have some lag to react and solid state power electronic solve this issue. On LV AC lines Metaloxide protection is also used. This is kind of a resistor which changes resistance respect to voltage level and conducts the surge current to ground. Many type of performance characteristics can be implemented. For fast reaction, solid state(power electronic) switches provide operation in nanosecond range. Mechanical actuators can operate in around 15 ms in best case. Passive elements such as capacitors have instant effect.

3. Modelling approach

Modelling approach assumes the simulated low voltage transient spikes from the previous study of the project (Subedi & Lehtonen, 2017). These voltage forms are approximated to PSCAD software and a generic LV grid model is built for. Power electronic load, supressing capacitor and DC protection are inspected on performance to the line conducted phenomenon.

Metal oxide surge protector is modelled with default characteristics of PSCAD which simulates ASEA XAP-A metal oxide surge arrester.

Table 1. Default I/V characteristic of MO surge arrester in PSCAD

I	V
0.001	1.100
0.01	1.600
0.1	1.700
0.2	1.739
0.38	1.777
0.65	1.815
1.11	1.853
1.50	1.881
2.00	1.910
2.80	1.948
200.0	3.200

The actual model of the MO is done with piecewise linear characteristic curve

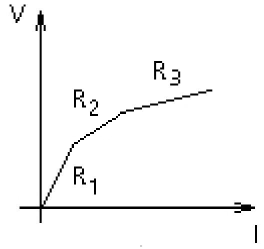

Figure 3-1. Principle of modelling nonlinear resistance in PSCAD

A simple DC load modelled into PSCAD with clamping style protector in DC bus is presented in Figure 3-2.

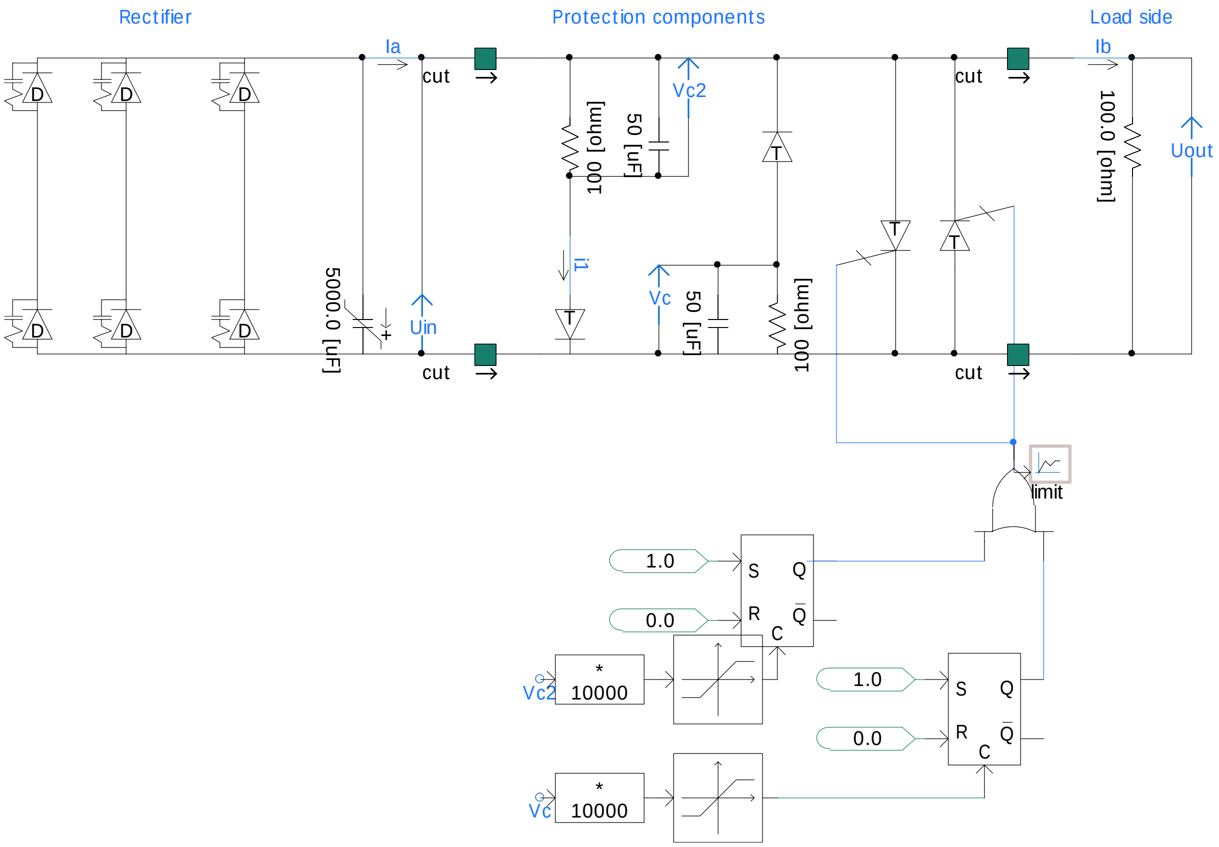

Figure 3-2. Circuit diagram of DC load in PSCAD with crowbar or clamp style protection

Rectifier parametrization in the model uses default values found in PSCAD main library.

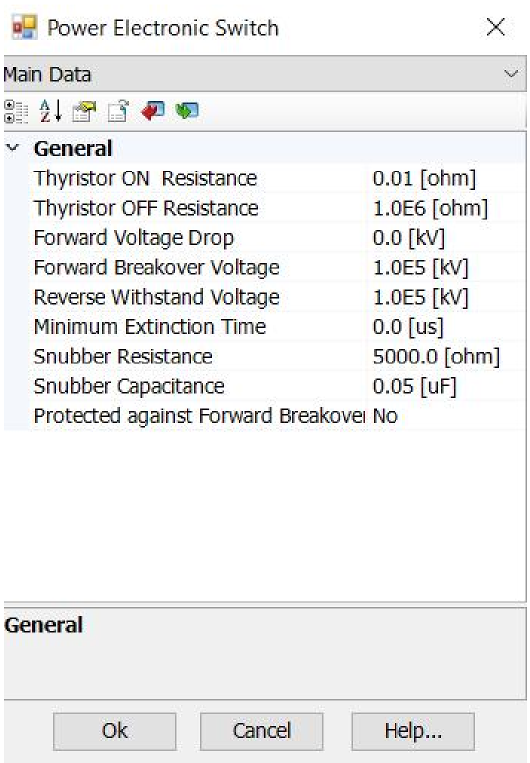

Figure 3-3. Rectifier diode settings in PSCAD

For the clamping circuit, diode forward voltage drop is used and set to 680 volts. As difference to normal crowbar circuit, the model has double amount of components to take account both polarities in the voltage spikes. Traditional crowbar short circuits the current to ground.

LV AC feeding system has ideal voltage source and Power cable Pi-model with following parameters:

Table 2. Power cable parameters for Pi-model

Positive Sequence	
+ve Sequence Resistance	.1781598E-4 [ohm/m]
+ve Sequence Inductive Reactance	.31388E-3 [ohm/m]
+ve Sequence Capacitive Reactance	273.5448 [Mohm*m]
Zero Sequence	
Zero Sequence Resistance	.2952201E-3 [ohm/m]
Zero Sequence Inductive Reactance	.1039898E-2 [ohm/m]
Zero Sequence Capacitive Reactance	414.1642 [Mohm*m]

Length of the cable is used as one variable in testing.

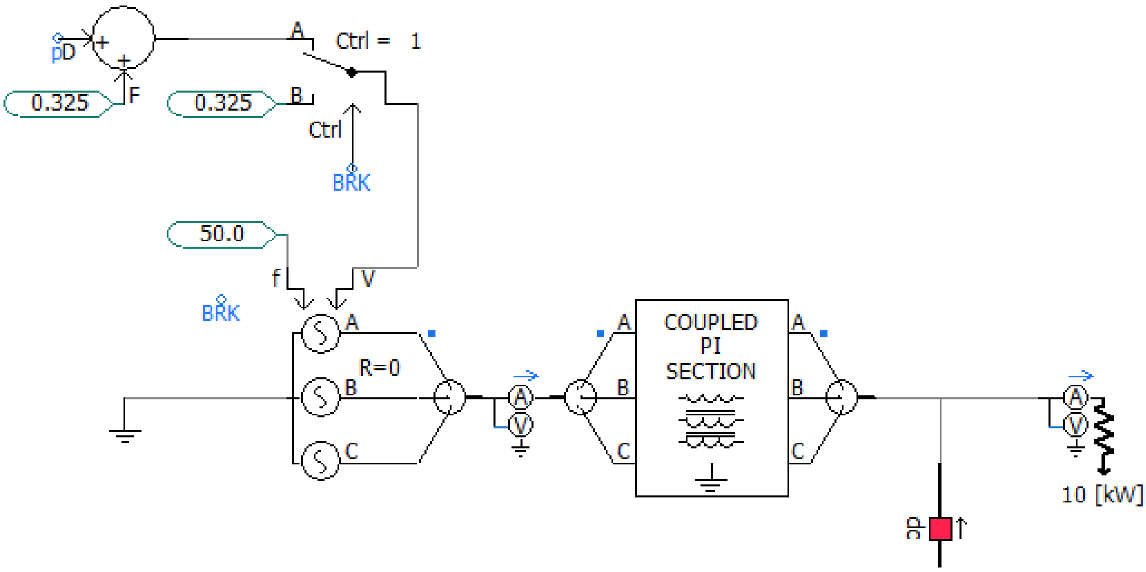

Figure 3-4. Low voltage AC grid feeding the power

Surge voltage is injected to LV AC side as separate signal on top of nominal voltages.

Battery model was also developed for the simulations. Step response of lead acid battery was presented in (Tenno, Tenno, & Suntio, 2004):

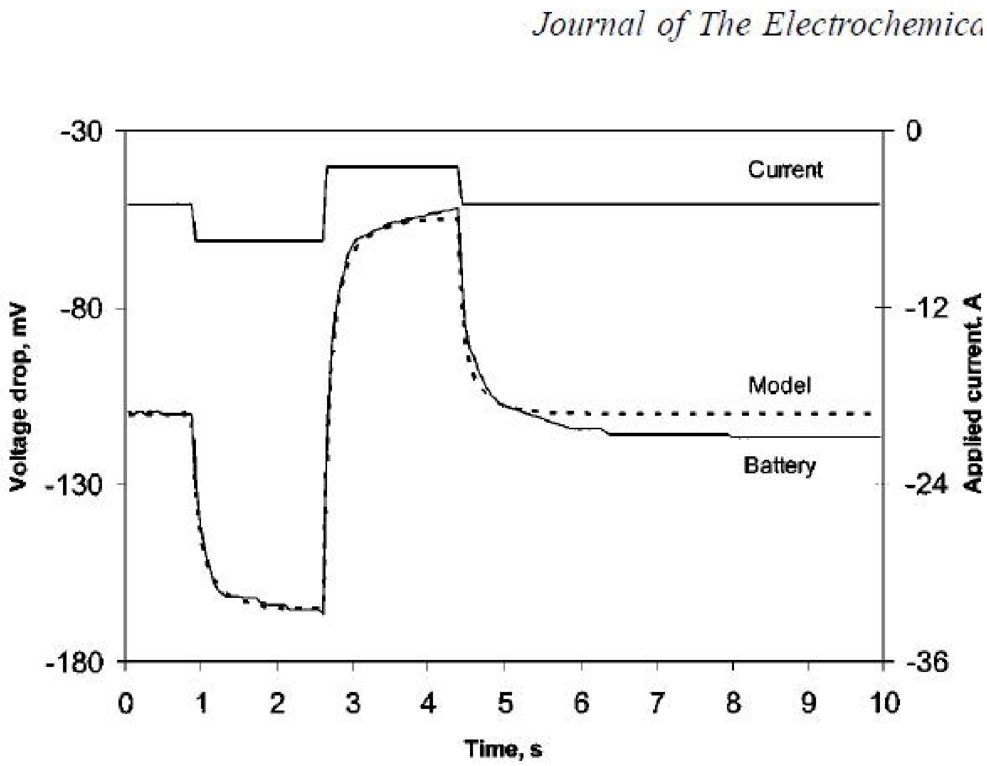

Figure 3-5: Lead-acid battery step response curve.(Tenno et al., 2004)

The continuous black like of step response of voltage from previous figure is used as a reference in the simulation.

Following circuit diagram of battery model was developed to PSCAD platform.

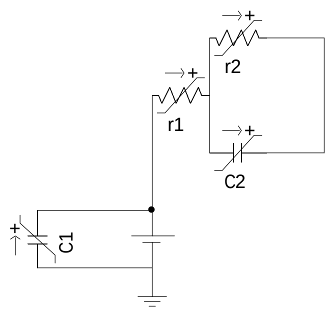

Figure 3-6: Circuit diagram of the battery model

Voltage source of the battery model is Shepherd model of a battery included into PSCAD main library. The purpose of the other components is to improve dynamic behavior of the battery. This was selected to be done as initial testing revealed that there was no dynamic behavior observed with the standard model in 1-2s load steps.

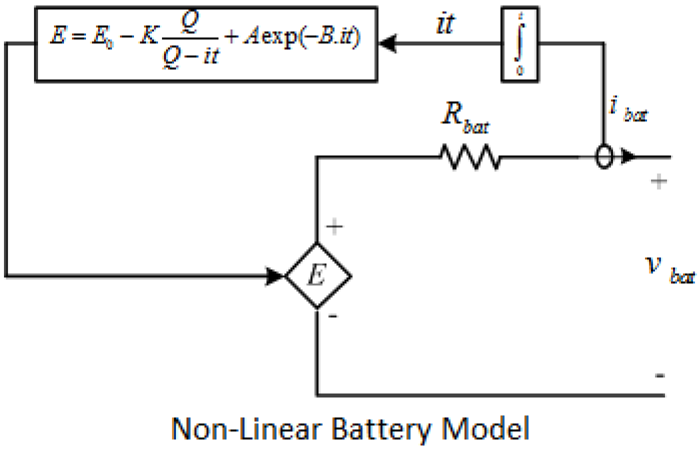

Figure 3-7:Shepherd model in PSCAD library

Adjusted input data for the model

Nominal voltage: 0.540 kV

Voltage level is set to this level so that there is no drain on battery using passive rectifier bridge. Fast lightning current made model quite slow and modelling active bridge control system and balancing them would require much longer simulation time.

Rated capacity: 0.0177 kAh
Initial state of charge: 80%

R1: 0.0522 Ω
R2: 3.6237 Ω
C1: 2.85714 MF
C2: 3.54634 MF

Following step response (Figure 3-8) was achieved with the additional components when simulated with nominal 17 A current. Idea was to get same kind of performance as with measured data in Figure 3-5.

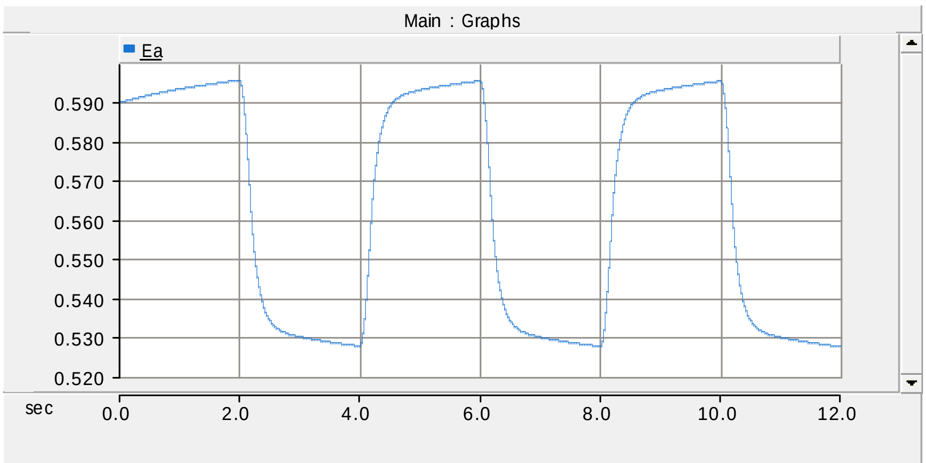

Figure 3-8: Step load response of the model with additional components

4. Cases inspected

Voltage spike profiles according to cases in (Subedi & Lehtonen, 2017) and load type(passive and power electronic) are used. Individual studies include reference case with no protection or load, power electronic load without protection, clamp style crowbar protection, metal oxide protection and a battery system buffering the load.

Following simulation results of voltage profiles are used as references for the protection simulation.

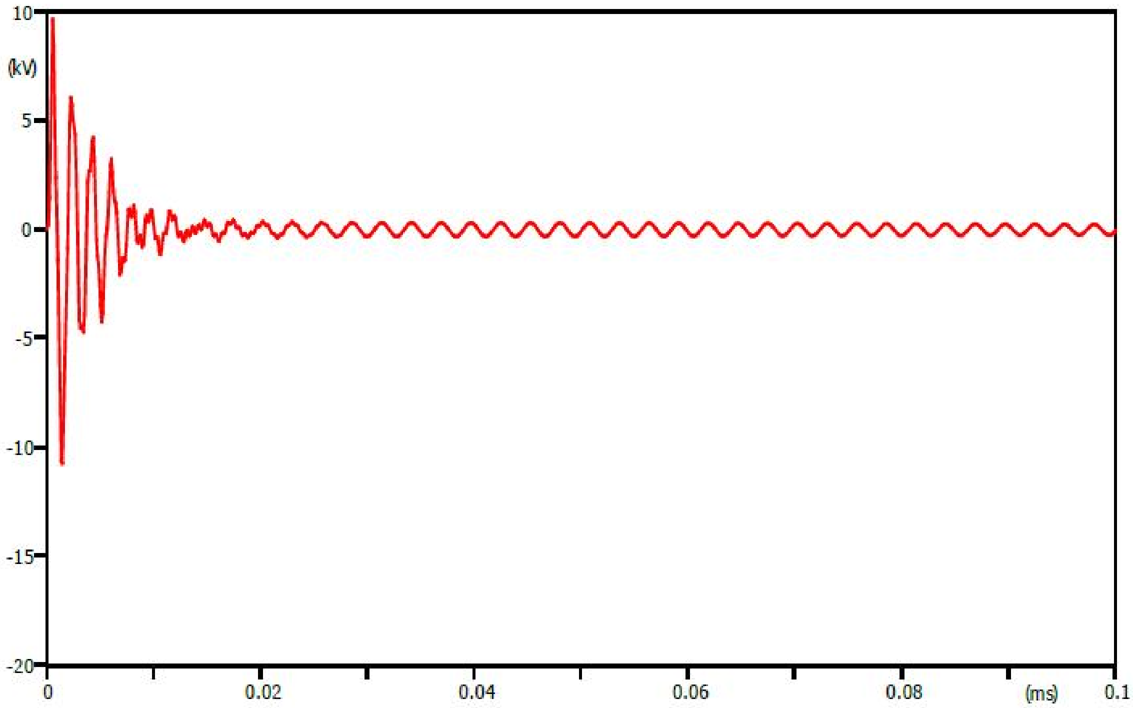

Figure 4-1. Voltage at 0.4 kV side at simulations in (Subedi & Lehtonen, 2017) with strike to 400 kV system and surge protection in 400 kV side.

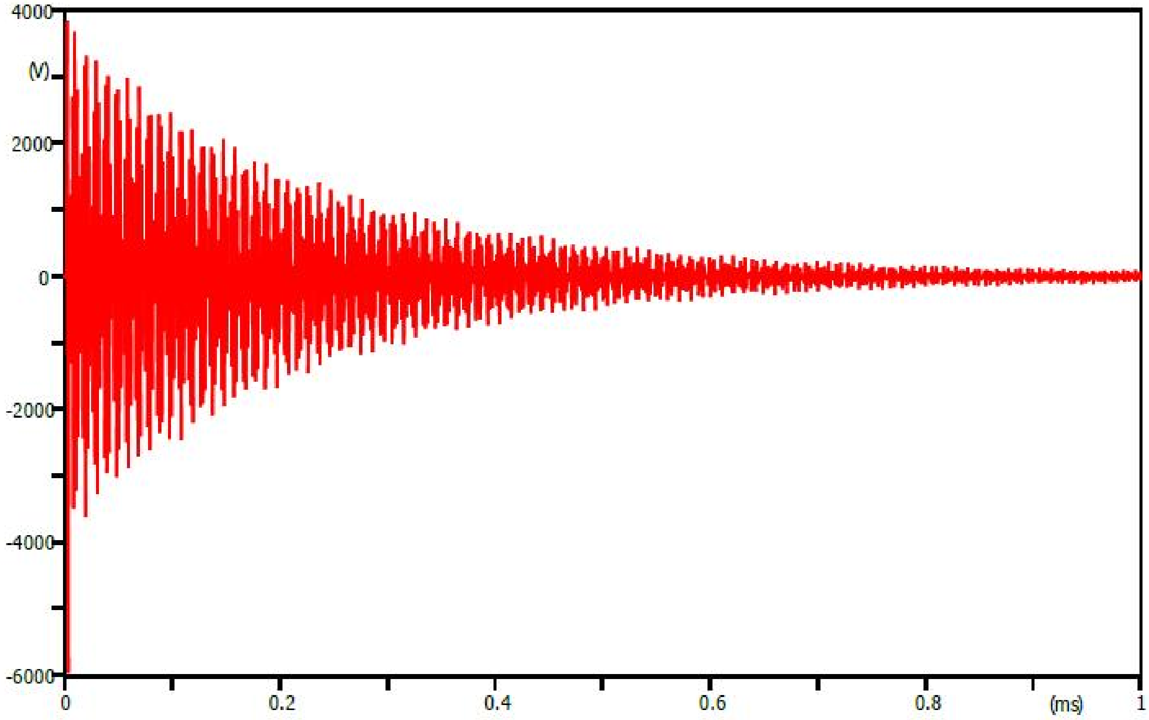

Figure 4-2. Voltage at 0.4 kV side at back flashover simulation in(Subedi & Lehtonen, 2017) with 400, 15.75 and 6 kV surge arrestors.

4.1 Base case with no protection

In base case, there is only 10 kW AC resistive load and 1m connection wire to reflect worst case. Following voltage curves were simulated to mimic the phenomenon in (Subedi & Lehtonen, 2017).

Voltage profile of 400 kV direct strike with high voltage surge arrestor of LV system

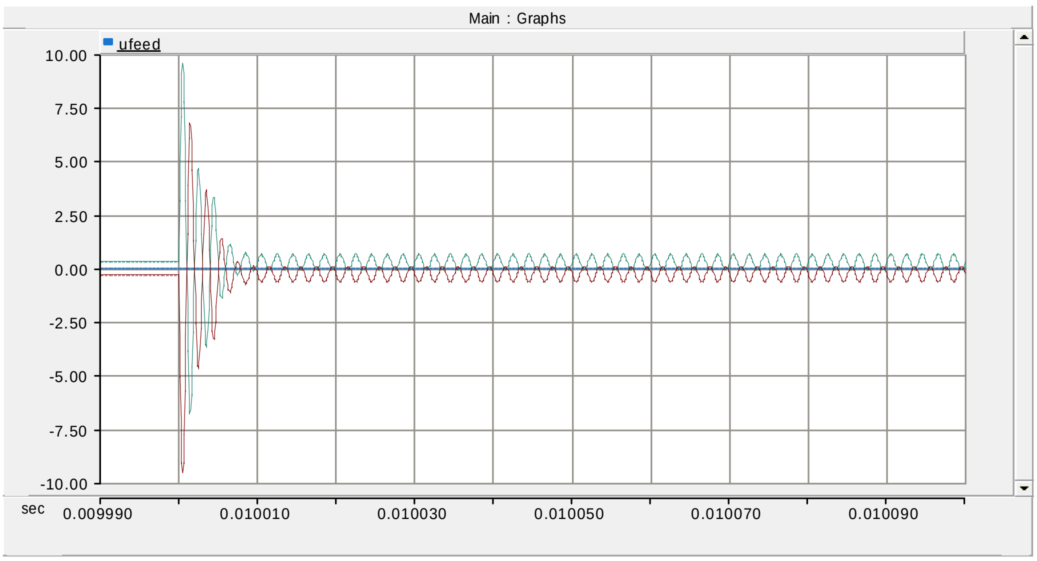

Figure 4-3. Voltage at LV AC system in 400 kV direct strike with stabilized voltage fluctuation excluded

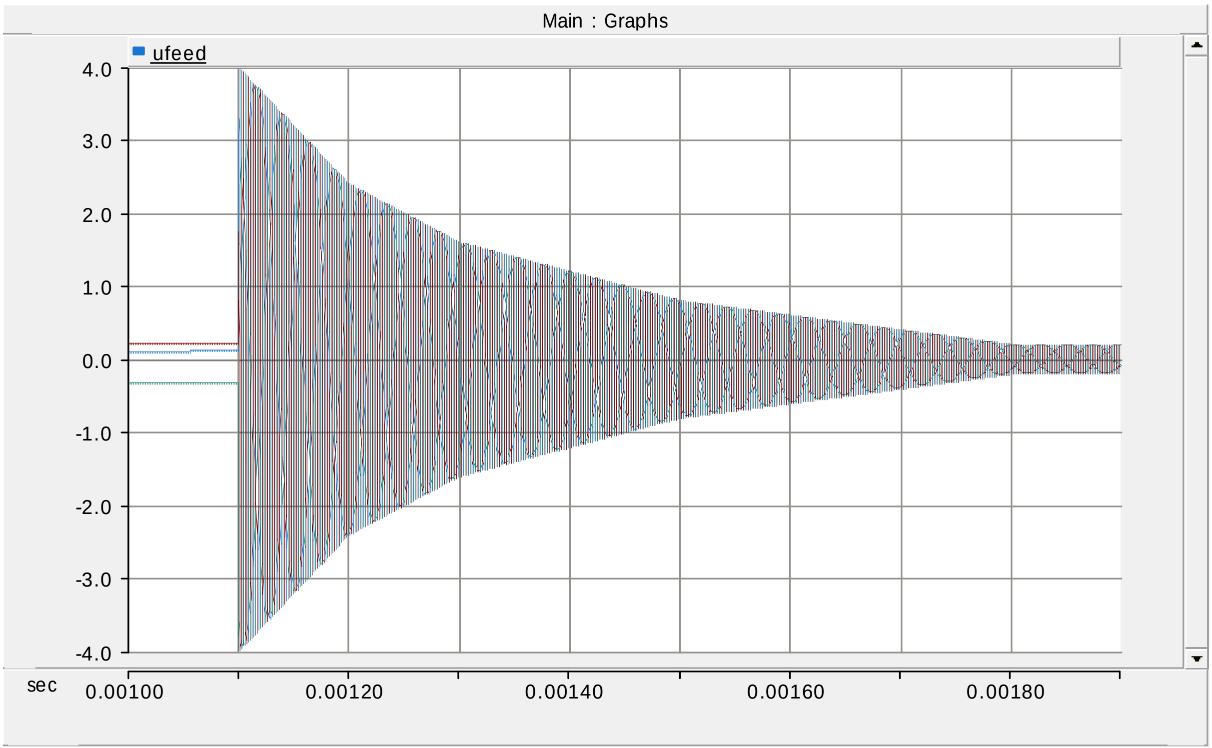

Figure 4-4. Voltage at 0.4 kV side at back flashover simulation

4.2 Metal oxide protection installed at LV side

Metal oxide protector with default curve and nominal protection voltage at 230 V (single phase AC)gives following results. MO protection is connected between phases and ground. Nominal peak voltage for 230 V AC line is 325 V. With the protection, maximum peak is 450 V as presented in figure 4.5.The lowest surge protection class is 500 V therefore this is adequate overvoltage level. More specifically IEC/EN 61000-4-5 requires AC installations on heavy industrial environments to withstand 4 kV line to ground surge voltage.

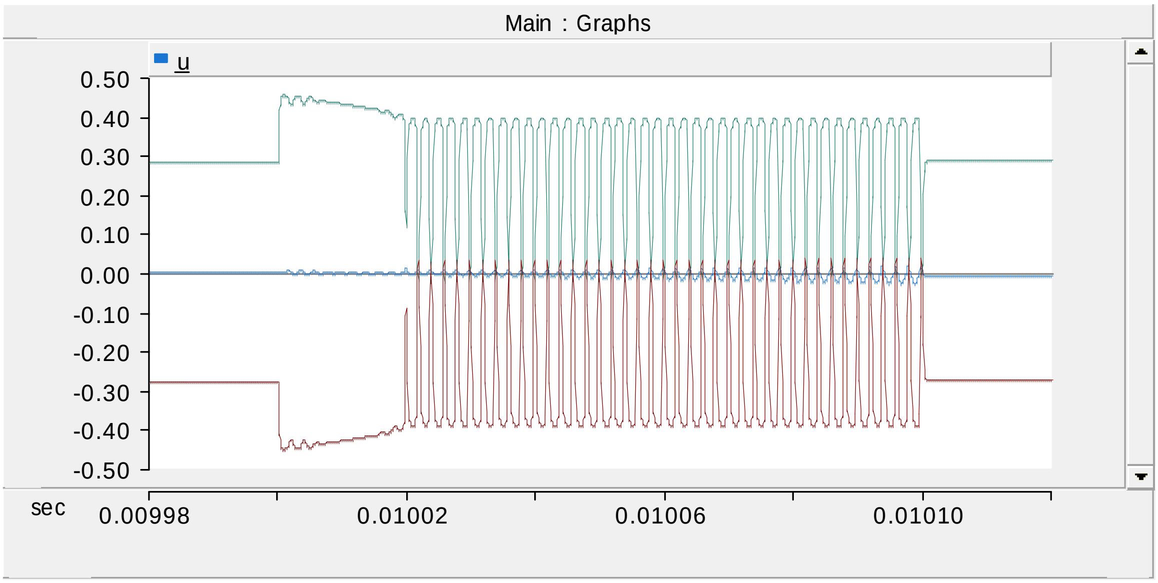

Figure 4-5. Load voltage with MO protection at LV AC system in 400 kV direct strike

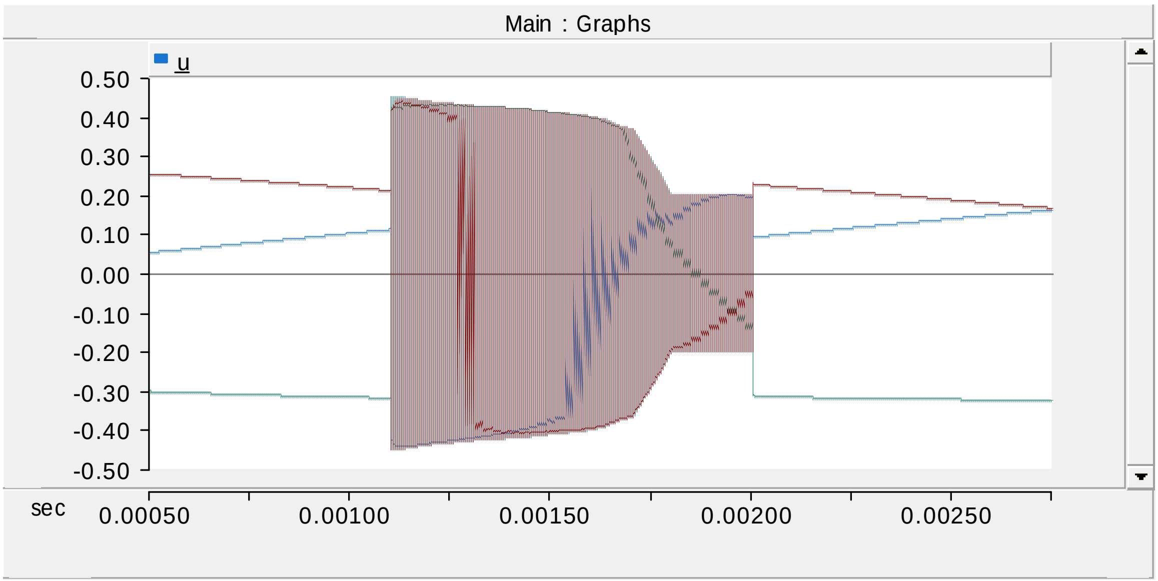

Figure 4-6. Load voltage at 0.4 kV side at back flashover simulation with MO protection

4.3 Power electronic load damping effect on voltage

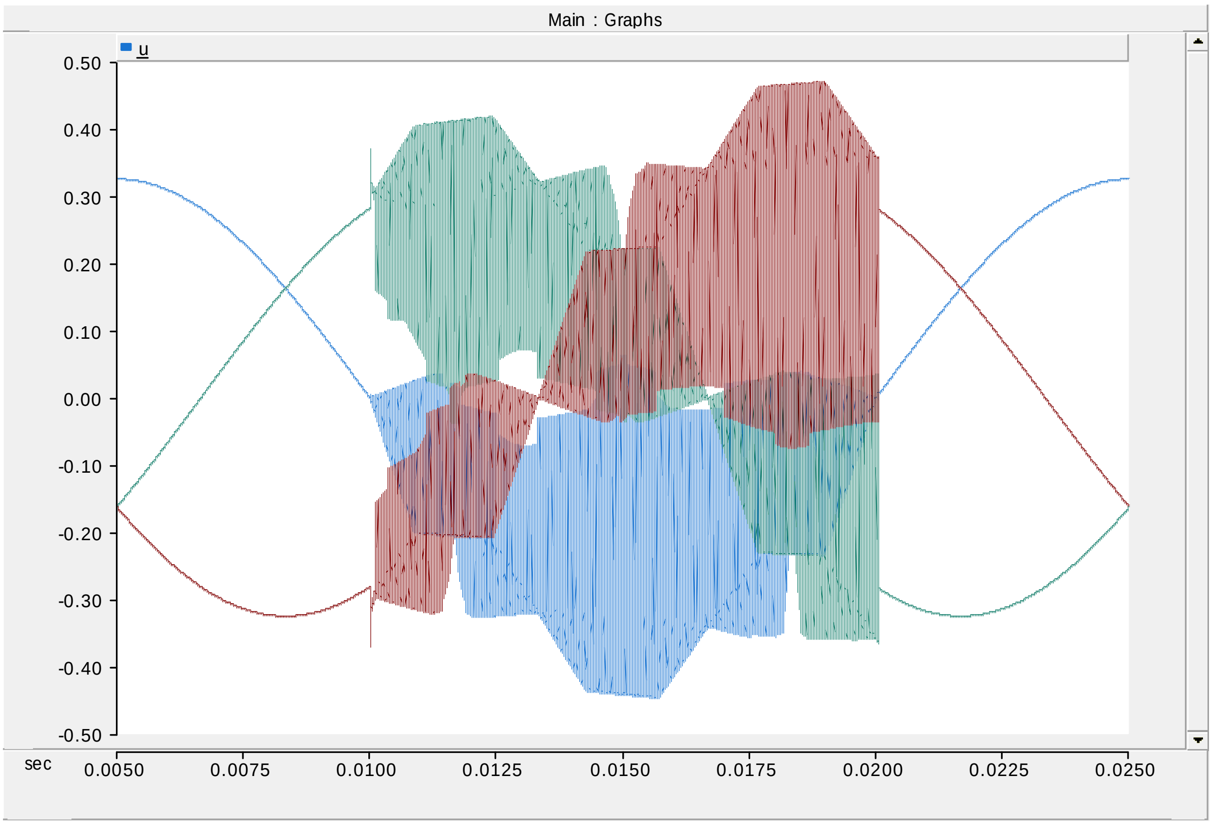

Figure 4-7. Load voltage with Power electronic load at LV AC system in 400 kV direct strike(drawing resolution does not cope here with fast fluctuations)

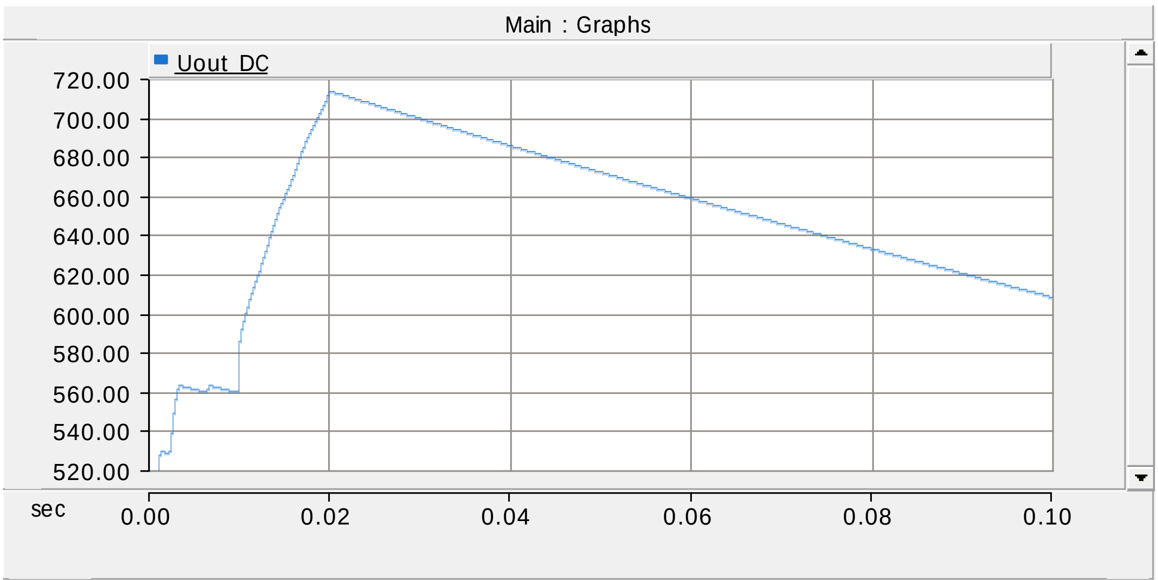

Figure 4-8. Power electronic load DC feed voltage system in 400 kV direct strike

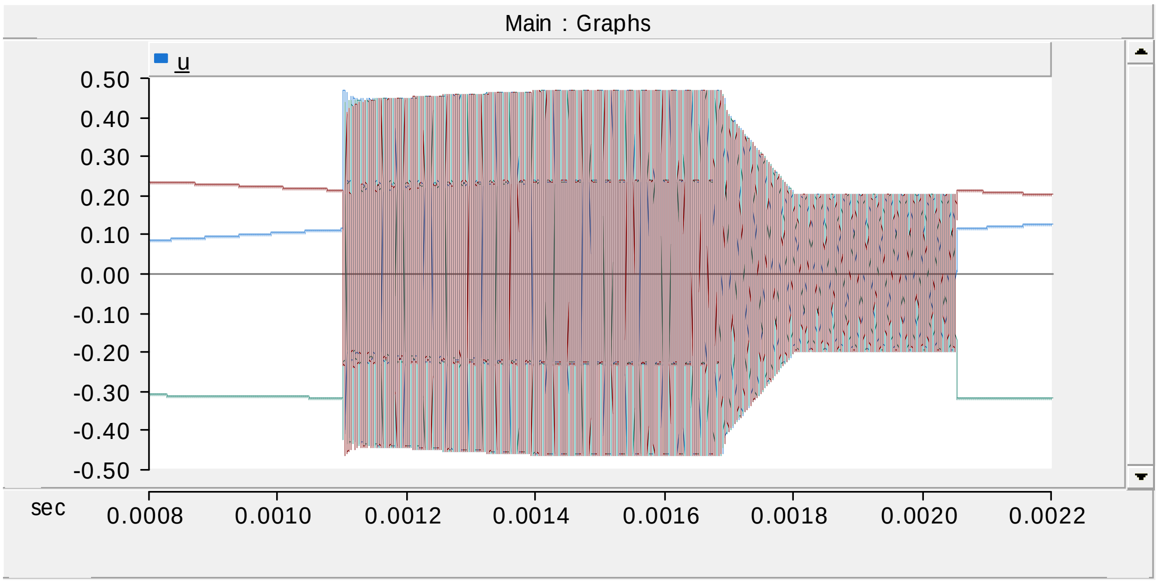

Figure 4-9.Load voltage at 0.4 kV side at back flashover simulation with power electronic load connected

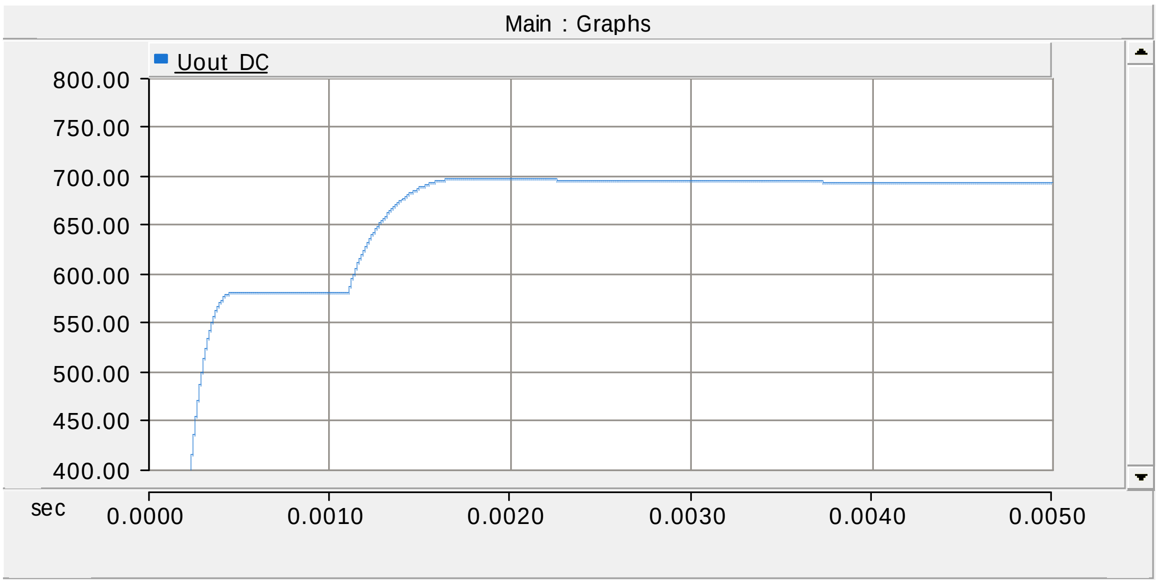

Figure 4-10. DC load voltage at back flashover simulation with power electronic load connected

4.4 Clamp style combined protection device

The clamp style protection devices is displayed in Figure 3-2. The idea is to short-circuit a DC bus when overvoltage occurs and break the current afterwards. This type of protection does not suit to loads that cannot allow short interruption in supply voltage when protection activates. However there is no problem if load is disconnected with battery still connected in UPS system.(disconnection is made between grid and battery and not between battery and grid)

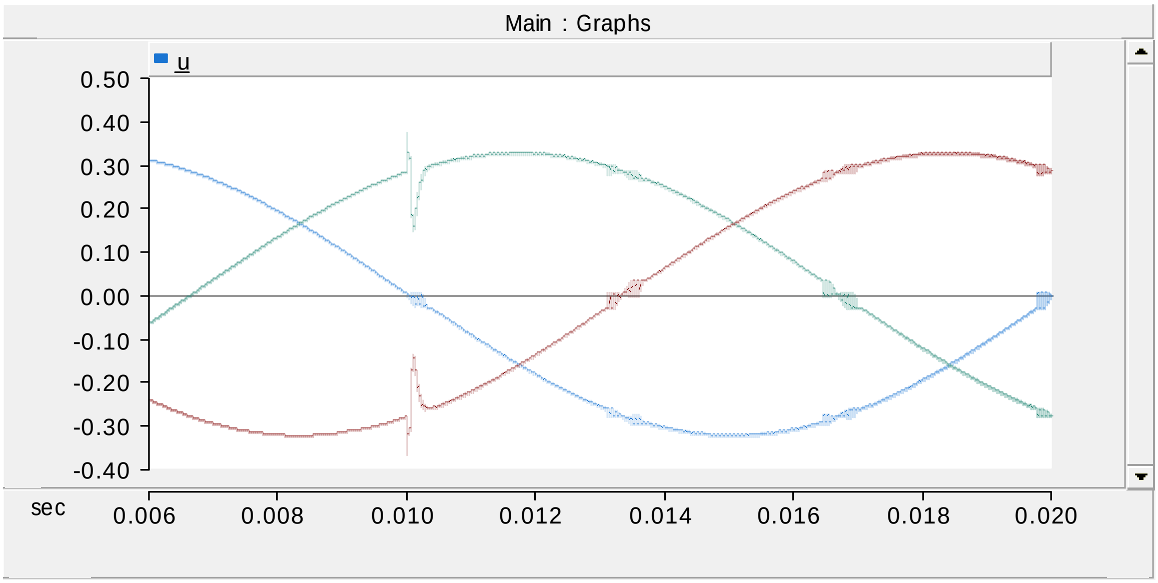

Figure 4-11: Load voltage at 0.4 kV side at direct strike simulation with clamp style protection installed

The protection device reduces greatly the voltage also at AC side of LV grid.

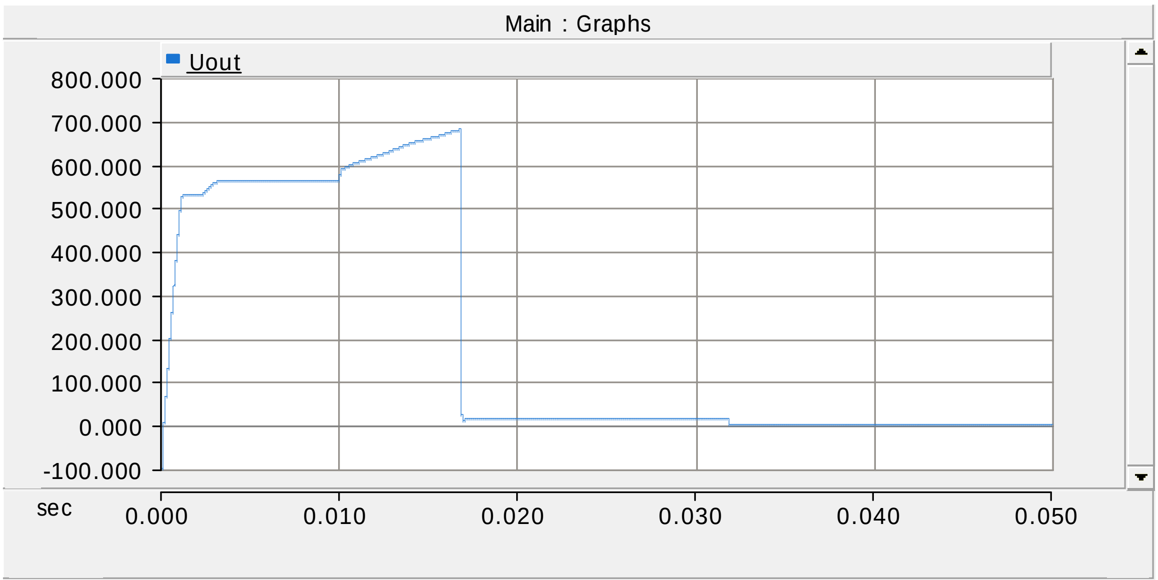

Figure 4-12: DC load voltage after the protection device

When threshold voltage is reached, the power electronic clamp shorts the DC load and after some time the overcurrent mechanical breaker disconnects the load. Voltage rises to threshold level of 680 V which was set as forward voltage drop.

4.5 Battery model included into DC bus

Because UPS units are very important aspect of LV systems of nuclear power plants, battery model is also good to include into simulations. Main circuit layout of Forskmark for example looks like following(battery systems marked as gray blocks) (Koshy, 2010).

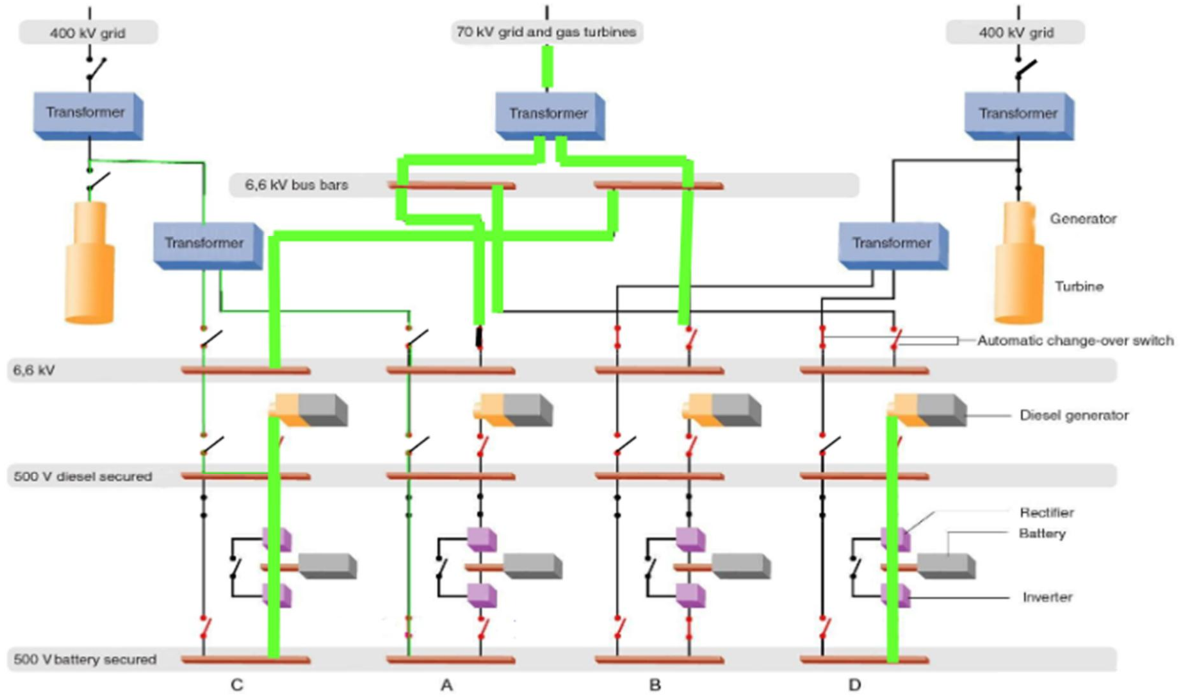

Figure 4-13: Forskmark electric system (Koshy, 2010)

Lead acid batteries are still the battery type used in UPS-devices in most applications. The used battery model was presented in Figure 3-6 and Figure 3-7.

When battery is added into the DC bus, the protection circuit won't even activate as battery dampens the voltage spike before the activation threshold. The DC voltage is displayed in Figure 4-14.

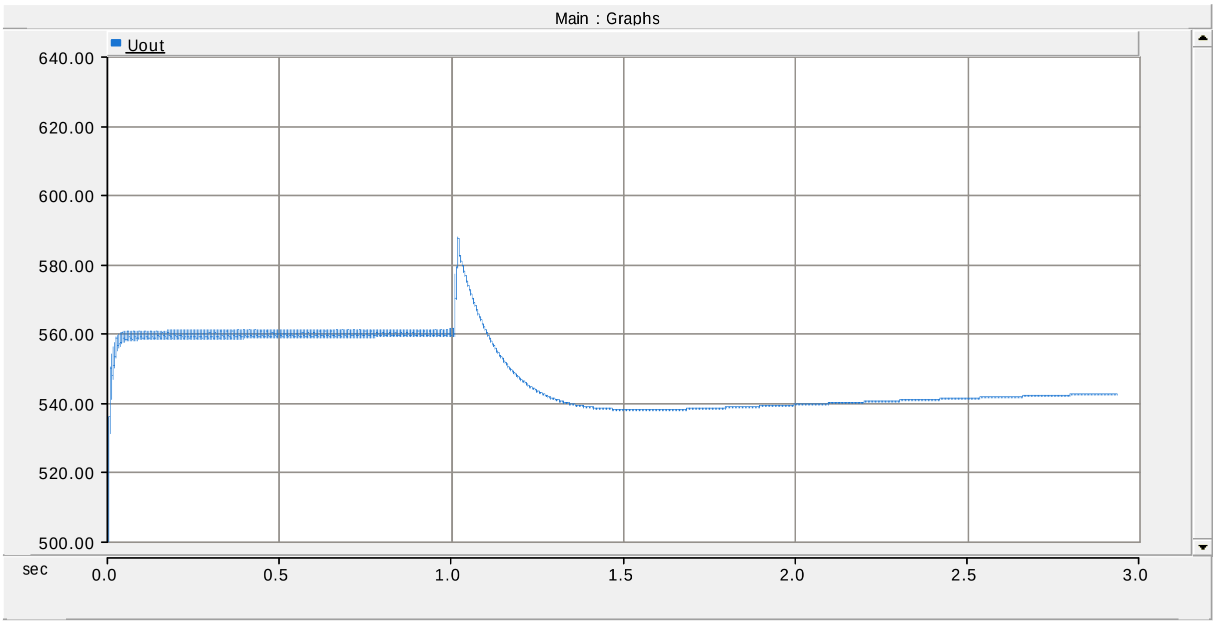

Figure 4-14: Load voltage with battery connected in direct 400 kV lighting strike

While battery buffered voltage rise, overcurrent protection of the battery disconnected theload and battery from the rectifier. Here battery stays connected to the load constantly via load DC bus but the bus connection between battery and rectifier is cut on grid side.

4.6 Damping effect of cable length

Short study was also made with simulator to inspect effect of cable length.

Reference case was with only 1m length from the fault voltage:

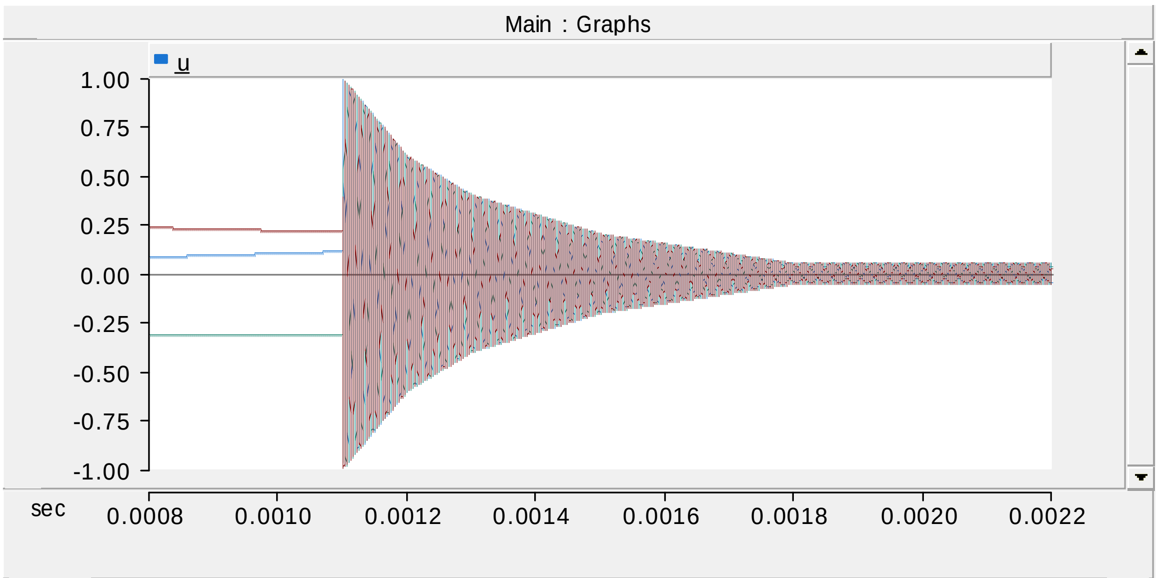

Figure 4-15. Voltage at 0.4 kV side at back flashover simulation 1m cable

With 10m cable, voltage profile is following:

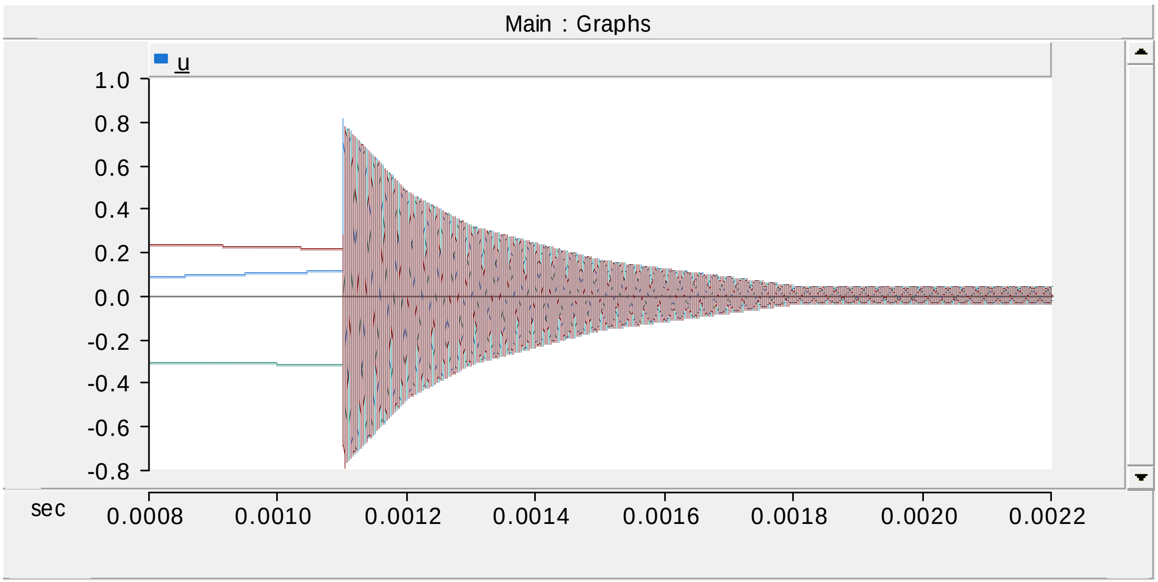

Figure 4-16: Voltage at 0.4 kV side at back flashover simulation 10m cable

And with 100m cable displayed in Figure 4-17

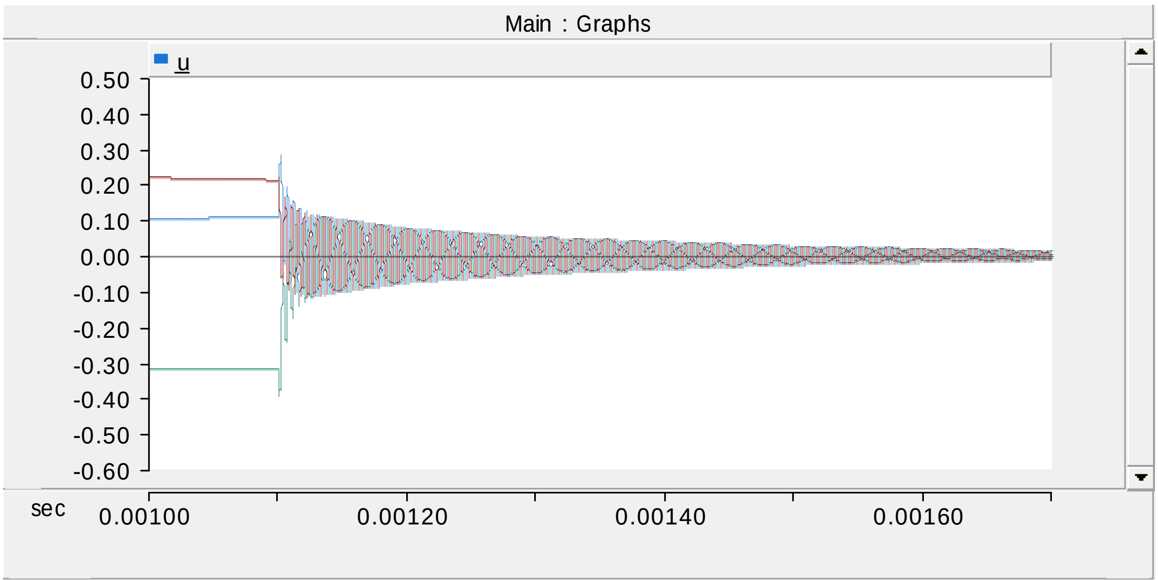

Figure 4-17: Voltage at 0.4 kV side at back flashover simulation 100m cable

Results indicate that maximum voltage that load experiences lowers if distances are long. It is however questionable is there any reason to take this into account in design as overvoltages could be directed to load in many other ways than supply cables.

5. Results and conclusions

The effects of direct lightning strike and flashover strike to 400kV system of nuclear power plant was inspected for perspective of low voltage power electronic devices. Protection methods were simulated with PSCAD transient simulator. The devices simulated were, metal oxide protector, three phase rectifier load and clamp style protection device with over-current protection and a battery. Metal oxide protector was effective to limit over voltage but some effects were noticed still at DC bus as rise in bus voltage. The connection of power electronic load solely already limited the overvoltages in LV AC point near the load. This effect comes from capacitance in the load to buffer the rectifier voltage. There is also protective capacitor over the rectifier components(in this case diodes) to protect them from overvoltages and they also help to dampen the overvoltages at DC bus. Battery also dampened the overvoltage so much that clamp type protection did not even activate. It has to be said that there is uncertainty of battery behaviour in very fast transient phenomena as most of measurements and models do not focus on this but it is very clear that dampening effect is considerable. In addition cable length between the fault and load dampens the voltage experienced by the load but overvoltage can occur from many other ways than main feeding cables so this is not reason to lower the other protection method requirements. Further study should be done on active bridge rectifiers to accurately simulate trickle charging of ead-acid battery which experiencing overvoltage surge. Also lab test could be done to characterise battery behaviour in very fast transients as there is not really material on this available.

6. Recommendations

Results indicate that capacitors are very effective at damping fast transient overvoltages. Because most DC rectifiers are based on active bridge technologies, it is small effort to also include protective functionalities such as overvoltage and over-current protections cutting the power electronically in faults. Although mechanical breakers are effective devices, they have operational delay for noticing the fault and acting. Therefore some passive protective methods could be used such as clamp type protection or additional capacitors. This study points to that capacitors are good solution for lightning overvoltage protection for power electronic devices. More broad usage of them in protection concept should be studied more on many other aspects such as potential contribution to faults in probabilistic manner.

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